Modeling carbon sequestration with CO_2Fix and a timber supply model for use in forest management planning

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[1]*Faculty of Forestry and Environmental Management, University of New Brunswick, P.O. Box 44555, Fredericton, New Brunswick, Canada E3B 6C2 (e-mail: eric.neilson@unb.ca);* [2]*Northern Forestry Centre, Canadian Forest Service, Edmonton, Alberta, Canada T6H 3S5.* *Received 20 October 2004, accepted 11 April 2005.*

Neilson, E. T., MacLean, D. A., Arp, P. A., Meng, F-R., Bourque, C. P-A. and Bhatti, J. S. 2006. **Modeling carbon sequestration with CO_2Fix and a timber supply model for use in forest management planning**. Can. J. Soil Sci. **86**: 219–233. Carbon (C) dynamics and forest management have become integrated in recent years, largely due to the Kyoto Protocol stipulating that forest C changes may be accountable in an emissions framework. A C stock modeling framework for forest managers is introduced in this paper. Empirical growth and yield models are used to develop sustainable timber supply for forest companies. These models use linear programming to solve the complex mathematical problem of timing and allocation of forest harvest and silviculture interventions. In this paper, we evaluated the effects of "business as usual" forest management versus management objectives to maximize C sequestration. Goal programming was used to minimize the deviation of two goals for C forest management: maximizing C in the forest, and maximizing the return on investment (net present value of forest timber products). Species-specific wood-to-C content conversion factors were used to parameterize the amount of C in forest stands on Canadian Forces Base Gagetown forest lands in New Brunswick, Canada. Goal programming reduced the loss of revenue associated with increasing C stocks in the forest. Partial harvesting and high valued end-products tended to increase C stocks and provided a higher return on investment in the simulations.

Key words: Carbon stock modeling framework, forest, goal programming, partial harvesting, timber supply

Neilson, E. T., MacLean, D. A., Arp, P. A., Meng, F-R., Bourque, C. P-A. et Bhatti, J. S. 2006. **Modélisation de la séquestration du carbone avec CO_2Fix et présentation d'un modèle de l'offre de bois d'œuvre pour une meilleure planification des travaux forestiers**. Can. J. Soil Sci. **86**: 219–233. Depuis quelques années, on intègre la dynamique du carbone (C) et l'aménagement forestier, principalement parce que le Protocole de Kyoto stipule que l'évolution des stocks de C forestiers pourrait entrer dans la comptabilisation des émissions de gaz à effet de serre. L'article que voici propose aux aménagistes forestiers un modèle permettant d'évaluer les réserves de C. Les auteurs recourent à des modèles empiriques de la croissance et du rendement pour parvenir à une offre soutenable de bois d'œuvre, à l'intention des sociétés forestières. Ces modèles font appel à la programmation linéaire pour résoudre le problème mathématique complexe qu'est la détermination du moment et de l'importance de l'exploitation forestière et des interventions sylvicoles. Les auteurs ont évalué les conséquences d'un aménagement forestier « ordinaire » et d'un aménagement ayant pour but de maximiser la séquestration du C. Ils se sont servis de la programmation des objectifs pour réduire au minimum l'écart par rapport à deux objectifs de gestion du C forestier : son optimisation et la maximisation du rendement des investissements (valeur nette actuelle des produits de bois d'œuvre). Ils ont recouru à des facteurs de conversion bois-contenu en carbone pour des espèces précises afin de paramétrer le volume de C dans les peuplements des boisés de la base militaire de Gagetown, au Nouveau-Brunswick (Canada). La programmation des objectifs atténue les pertes de revenus liées à l'accroissement des réserves de C de la forêt. Lors des simulations, une exploitation partielle et la fabrication de produits finaux à valeur élevée ont tendance à augmenter les stocks de C et aboutissent à un meilleur rendement des investissements.

Mots clés: Modélisation des stocks de carbone, forêt, programmation des objectifs, exploitation partielle, offre de bois d'œuvre

Canada's ratification of the Kyoto Protocol means the country must meet by 2008 (Noss 2001) a CO_2 emissions target of 6% below 1990 levels (Intergovernmental Panel on Climate Change 2000; Kurz et al. 2002). Pending a government decision by 2006 on whether to include forest management in the accounting process, woodland owners may be obligated to contribute towards this emissions target and may have to provide an account of the C stocks on their landscapes (Kyoto Protocol section 3.4). Forest management decisions will impact the C budget (overall amount of C in vegetation and soils) of forested landscapes (Kurz et al. 2002; and elsewhere Peng et al. 2002a) in the short-, mid- and long-term. Canadian forests are estimated to contain from 200 Gt C (Kurz et al. 1992) to 224 Gt C (Dixon et al. 1994) of the total 1150 Gt geo-forest C pool (Dixon et al. 1994). Forests consequently contribute to the estimated 2.3 Gt C yr^{-1} (Dixon et al. 1994; Houghton 2003) removed through photosynthesis by terrestrial ecosystems from the biosphere (Dixon et al. 1994; Masera et al. 2003; Houghton 2003) and play a major role in the global C cycle. Should Canada include forest management under the Kyoto

Abbreviations: CFB, Canadian Forces Base**; CWD**, coarse woody debris; **FDS**, forest development survey; **GIS**, geographical information system; **GP**, goal programming; **NBDNR**, New Brunswick Department of Natural Resources

Protocol, a national strategy to increase C sequestration in the Canadian forest sector could help to meet its emissions cap by offsetting greenhouse gas emission from other economic sectors.

Several different process-based, empirical, and hybrid (combination of process-based and empirical) models have been developed to account for forest C dynamics. Examples include the European forest information scenario (EFISCEN) model (Karjalainen et al. 2002), an empirical model; the ecosystem net primary production simulation model FORECAST (Kimmins et al. 1999; Seely et al. 2002); European CO_2Fix model (Masera et al. 2003); CENTURY 4.0 built upon the FORSKA2 model (Parton et al. 1987; Price et al. 1999); TRIPLEX 1.0 (Peng et al. 2002b); C Budget Model of the Canadian Forest Sector (CBM-CFS) (Kurz et al. 1992); and others. The above models are largely process-based, used in scientific studies and are unsuited for integration with forest management plans. Some were designed to predict global C levels for 300 or more years into the future, such as FORECAST (Kimmins et al. 1999) or CENTURY, which was developed to simulate climate change effects on boreal C pools of Canada (Price et al. 1999). In this study, CO_2Fix was used to simulate the C dynamics of forest stands.

Forest managers have detailed inventory information on the conditions of their landscapes in terms of merchantable timber volume. Merchantable volume is clearly related to the amount of living biomass in a stand, yet there are no accepted functions linking merchantable volume to the amount of total ecosystem C in stands over time. The age of the community of tree species, the past disturbance history of the stand, and the amount of coarse woody debris (CWD) all affect the relationship between C and merchantable volume. Young stands with very thick canopy closure would likely have little merchantable volume but, depending on the recent disturbance history of the site, could have large quantities of CWD, dead trees ("snags") and other biomass, which would not be considered "merchantable". As the stands age, however, and the number of stems per hectare decreases, the relationship of merchantable volume to C becomes more direct. The majority of the living biomass in a mature, even-aged stand comes from the stems, branches and roots of the trees.

The objectives of this study were to (1) develop a framework of methods to facilitate the integration of C values into forest management planning, (2) apply these methods to a 110 000-ha area in New Brunswick, Canada, and (3) examine effects of partial cutting scenarios to retain C stocks on the landscape. Results and methods from this study should give forest managers the building blocks to develop strategic forest management plans with a projection of impacts of forest operations on the C stocks of their forested lands.

MATERIALS AND METHODS

Forest Characterization and Landbase Description

Canadian Forces Base (CFB) Gagetown is located (latitude 45°39′32″N; longitude 66°20′2″W) in southern New Brunswick, Canada. The landbase encompasses 110 000 ha of conglomerated forest lands, static impact zones used for military training and ecological reserves (Fig. 1). Stratification of stand types on CFB Gagetown was based on forest cover type and eco-district [New Brunswick Department of Natural Resources (NBDNR) 1996; Fig. 2]. The cover types were adapted from strata previously developed by NBDNR.

The landbase is divided into four discrete management zones. CFB Gagetown is a military training facility and as such, military training represents the primary land-use objective of the landbase. However, there is a 53 000-ha forest management zone (zone 4, Fig. 3) in which sustainable forest management is practiced. The landbase also hosts some ecological reserves such as the Nerepis Hills and the Nerepis River basin, in which no harvesting or military activities are supposed to take place. For the purpose of this study, we only used the forest management zone 4, as forestry practices were not in place in the other zones. C management in the other zones would be more suitably addressed by other methods, not found in this study, yet significant as this federal land will be accountable under the framework of the Kyoto Protocol.

Merchantable volume yield tables were developed from data collected from forest development survey (FDS) plots established by NBDNR. There were no FDS plots within the study area; however, there were FDS plots within the eco-districts overlapping the landbase. Eco-districts 25, 26 and 33 extend onto CFB Gagetown (Fig. 2). Data from plots in these areas were applied to stands on the base. Since hemlock [*Tsuga canadensis* (L.) Carr.] and larch [*Larix laricina* (Du Roi) K. Koch] stands existed on the base, but the number of plots for these strata in ecodistricts 25, 26, and 33 was insufficient for compiling yield tables, data from surrounding eco-districts were used.

The program STAMAN (STAnd MANager - Vanguard Forest Management Services 1993) was used to create merchantable volume yields. STAMAN requires at least five FDS plots in each stratum to generate a yield table. Strata with less than five plots were combined with a similar stratum, either by species or by eco-district, to obtain enough plots. For example, a spruce/tolerant hardwood stratum and a balsam fir/tolerant hardwood stratum might be combined to produce a softwood/tolerant hardwood stratum, or spruce/balsam fir strata from eco-districts 25 and 33 might be combined and applied to areas in both eco-districts. All of the strata and their descriptions are listed in Table 1 and examples of two curves are shown in Fig. 4a,b.

Once each stratum had at least five plots, the yield curves were processed by STAMAN and each yield curve was examined. If two strata with the same species in different eco-districts had similar yield curves, they were combined into one stratum. If the curves included plots that were quite different from all of the other plots (e.g., different yields), and if they had the correct species composition for those strata, the curve was assumed to be a poor representation of that stratum and was deleted.

Table 1 outlines the forest cover types and species composition within each stratum. The area of the landbase was

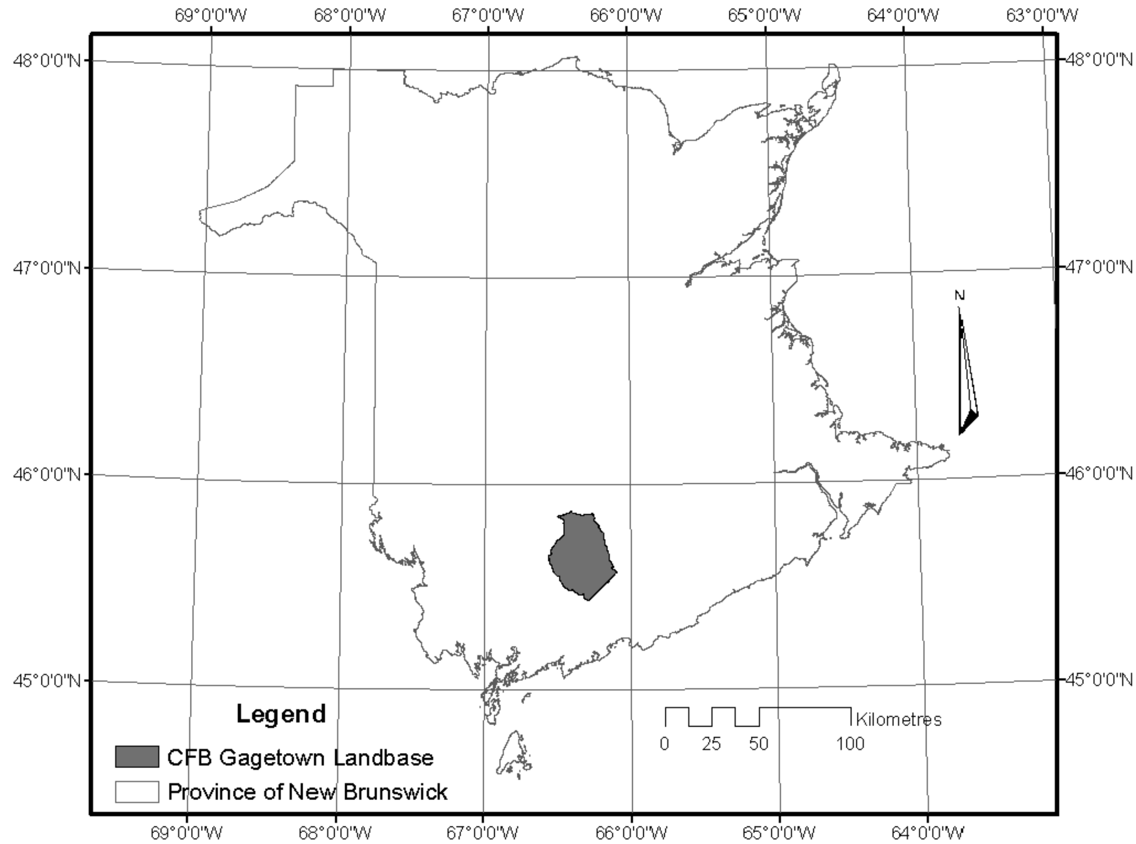

Fig. 1. The study area, CFB Gagetown, is located in southern New Brunswick, Canada and is 110 000 ha in area.

mapped using a geographical information system (GIS). Polygons denoting forest stands were obtained from the CFB Gagetown Forest Management Division. Each forested polygon was assigned a 5-yr age class based on aerial photography and GIS data scripts. Polygons were then mapped to one of the 21 strata by another data script in the GIS. The result was a spatially explicit forest inventory for management zone 4, with each forest polygon assigned an age-class and a merchantable volume yield table. With these data, it was possible to create an "area file" for input to the timber supply model Woodstock (Remsoft© Inc. 1999). The area file acts as initialization parameters for the timber supply model, depicting forest conditions at the start of the planning horizon in terms of area of stratum (ha) and age class of each forest polygon.

The Woodstock timber supply model "grows" the forest for a specified amount of time by evolving forest stands from assigned merchantable volume yield tables. Since volume yield tables are time-dependant functions, Woodstock can grow the forest for any specified amount of time. We used an 80-yr planning horizon, as this is the current required length in New Brunswick for strategic forest management planning. Woodstock uses embedded linear programming software to solve the complex objective functions that arise in the calculation and development of sustainable forest management plans. We used the MOSEK (Andersen and Andersen 2000) solving software as our linear programming solver.

The Woodstock model simulated stand development, including growth, death, and regeneration, as well as harvesting and silvicultural actions. CFB Gagetown uses the clearcutting harvesting system, 100% volume removal, as well as a partial cutting system in which 30% of the volume ha^{-1} is removed. We wanted to examine the ability of partial cutting to retain C stocks on the landscape, as opposed to clearcutting, which removes most, if not all, of the standing biomass. Depending on scarification techniques, site preparation could also remove much of the CWD on sites that were to be planted. The model can also simulate pre-commercial thinning and planting. Planting was only simulated on stands that had been clearcut. Planting clearcut stands resulted in even-aged structures, with higher than average growth rates (~ 5 m^3 ha^{-1} yr^{-1}) and high resultant volumes of timber at maturity (~ 200–300 m^3 ha^{-1}). However, planted stands may have shorter rotations, as they reach economic maturity earlier than naturally regenerated stands. Shorter rotation periods have been linked to lower C storage capabilities and we wanted to determine the effects of different management objectives on the resulting age-class structure of the forest.

Partial Cutting Simulation

Partial cutting was enabled in the model for most well-stocked stand types in the study area. Lee et al. (2002) have

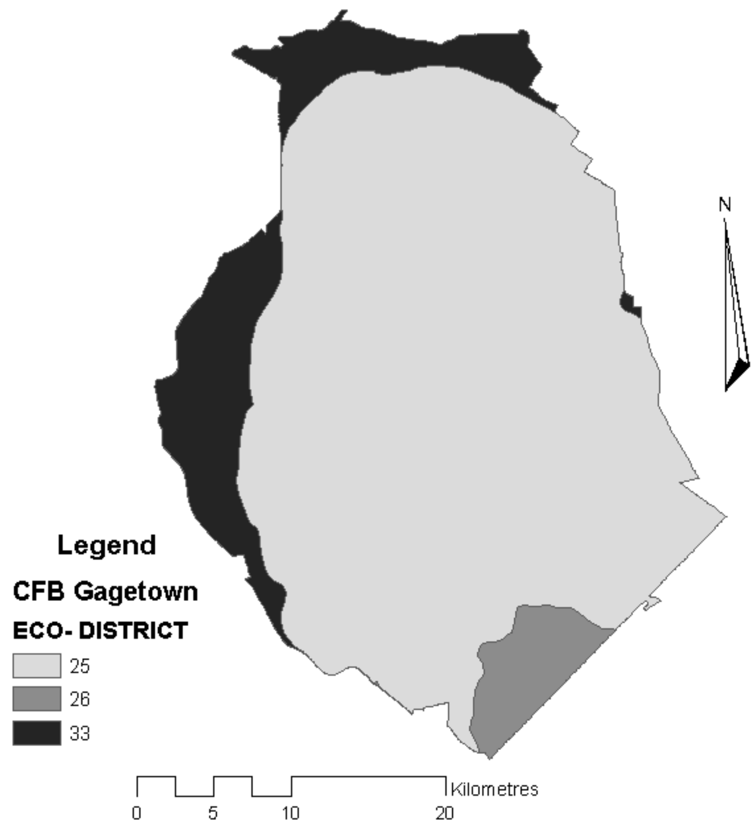

Fig. 2. Eco-districts on CFB Gagetown. Eco-district 26 is in the Nerepis Hills region and supports mixedwood ridges and elevations of up to 300 m. Eco-districts 25 and 33 have similar species composition and occupy lower elevations mostly below 100 m. Eco-districts were used to stratify the forest land growth and yield for input to the wood supply model.

shown that increased C sequestration was possible using a partial cutting harvesting system and we wished to test this postulate. Poorly stocked strata were deemed ineligible for partial cutting. Partial cutting was simulated in the model by a removal of 30% of the volume in stands at the first entry. Following the first entry, each stand was "locked" by the model for four planning periods (20 yr), meaning that no further silvicultural actions could take place for 20 yr following partial cutting. The model then simulated a second cut into each of the now partial cut stands and removed 30% of the total volume. Another 20-yr lock was enforced and the stand was grown until the third and final cut was done by means of a clearcut. Resulting forest stands were then planted, or allowed to regenerate naturally, depending upon the model prescription for the resulting area.

The previous paragraph described the "best-case" scenario with partial cutting, but there were cases where the model would be unable to make a second partial cut. In these cases, the stand was clearcut and transitioned to strata in regeneration stages. Partial cutting represented a harvesting option that balanced the need for revenue production and C sequestration objectives, as the method left most of the canopy closed and provided sustained litterfall from living vegetation. In general, partial cutting is a harvesting option that produces several benefits: it leads to the production of high value timber, maintains 70% of the growing stock on the ground at each cutting stage, and maintains closed canopy conditions for sustained litterfall and sheltered conditions on the ground.

Carbon Dynamics Model

Integrating C sequestration objectives into the timber supply context requires a systematic conversion of merchantable volume information into C sequestration information. To that end, Diaz-Baltiero et al. (2003) used a conversion factor of 0.2 Mg C m^{-3} of merchantable wood volume. We felt that this number is insufficient to address all the components that affect this conversion. Instead, work by von Mirbach (2000) produced a conversion factor of 0.4 for merchantable volume (m^3) to Mg C in mature stands. We used this number for all stands at age 60, and guided the volume-to-C conversion of any stand age with the CO_2Fix model (Masera et al. 2003), based on calibrations with known and assumed timber volumes as input, by stand type.

The CO_2Fix model yield calculations were further adjusted using local air temperature, and precipitation as additional input variables. These calculations were particularly useful in guiding the C and timber yield calculations that follow the clearcutting, thinning and partial cut operations.

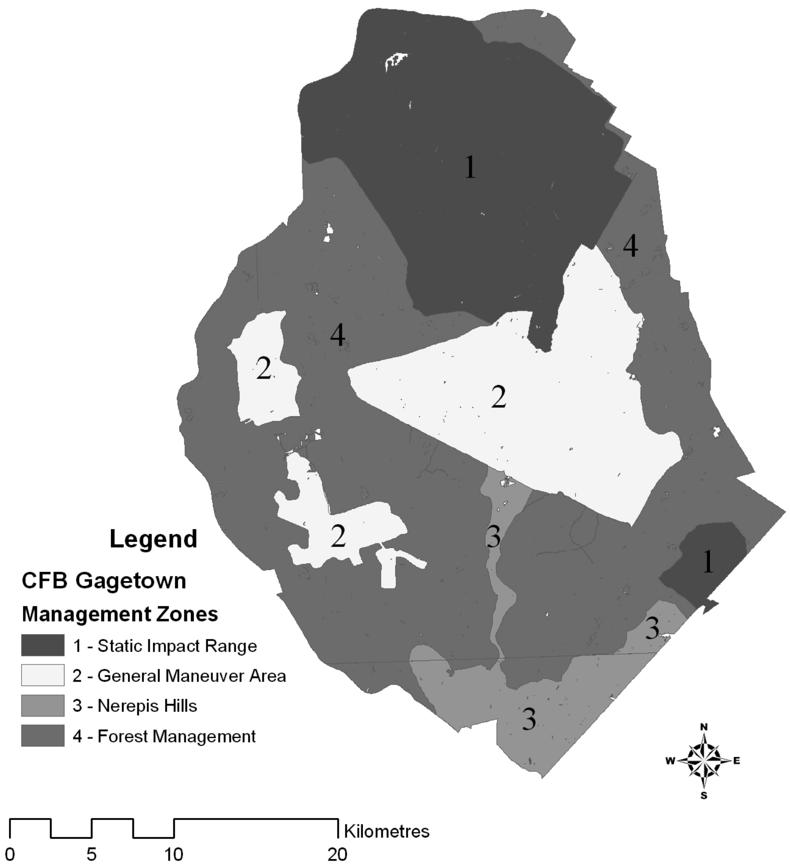

Fig. 3. CFB Gagetown is divided into four different management zones. The forest management zone is roughly 53 000 ha and is surrounded by static impact ranges, maneuver areas, and ecological reserves. The Nerepis Hills (zone 3) is an ecological reserve and thus no harvesting is conducted. This study examined the management of zone 4 only.

The CO_2Fix model generates numbers for net photosynthate production, and allocates this production to foliage, branches, stems, roots and litter. The model also calculated litter decomposition, useful for assessing the amount of C that accumulates on the forest floor over time, and is subject to changes as part of each silvicultural intervention. We decided, however, that the uncertainties surrounding soil C assessments could be more accurately addressed using other computational methods. Therefore, all soil C stocks (humus) as simulated by CO_2Fix were removed from further consideration. Examples of the resulting C yields and timber yields are shown in Fig. 4. In general, both timber and C yields were quite similar with respect to each other, as to be expected.

CO_2Fix is a multi-cohort C simulation model with the ability to produce C yields from known merchantable volume yields based on incremental (m^3 ha^{-1} yr^{-1}) growth of cohorts. We used CO_2Fix to simulate the C dynamics over time, of each of the 21 strata outlined in Table 1, to develop 21 C yields and 34 partial cut C yields. Roots in the model were simulated to grow as a function proportional to stem growth, as were foliage and branches. Mortality was simulated as a result of competition within the stratum and based on percent volume lost per 5-yr time period. The specifics of how CO_2Fix calculates each component of biomass per stratum were outlined in Masera et al. (2003). We used species-specific C density of a selection of tree species native to Canada from Lamlom and Savidge (2003). Allometric equations from Ker (1984) were used to calculate stem to branch and stem to root proportions. Data from the Fluxnet research program provided temperature and evapotranspiration parameters (C.P-A. Bourque, 2004, personal communication).

We used the CO_2Fix model because it was parameterized with the growth and yield data generated from FDS plots and because of its availability to be used freely over the World Wide Web. The C yield for each stratum was then used as input to the Woodstock timber supply model, such that all strata were related to time-dependant functions of merchantable volume and biomass. C yields followed similar growth shapes (Fig. 4c,d) as the merchantable volume yields from which they came (Fig. 4a,b). This allowed management actions (harvesting, planting and thinning) effects on C stocks of the forested landbase to be simulated by the Woodstock model. Because of the time-dependent biomass function and merchantable volume function, clearcut harvesting would effectively “reset” the harvested stratum’s merchantable volume to zero and a similar response could be simulated by the stratum’s biomass function. By sum-

Table 1. Forest strata and cover types of the CFB Gagetown forest management zone, as modeled by the timber supply model. Codes designate modeled stand type names

Strata (code)				
>75% softwood	50–75% softwood	25–50% softwood	<25% softwood	Species in order of volume[z]
Eastern cedar (EC)				eC, bS, bF, rM, rS, yB, tL, wB, wP
Eastern hemlock (EH)				hE, bF, rS, wS, rM, bE, yB, wB, pO
Other pine (OPINE)				rP, jP, wP, rS, bS, wS, bF, rM, wB, pO,
Pre-commercially thinned Balsam fir-spruce (PCT_SPBF)				bF, bS, rM, rS, wS, wB, sM, wP, jP, pO
Planted spruce (PLSP)				wS, bS, bF, wP, rP, rM, sM, wB, eC
Poor spruce (PSSP)				bS, rS, wP, eC, tL, bF, yB, wB
Spruce-fir (SPBF_25_33[y])				bS, rS, bF, wS, rM, wP, jP, eC, hE, wB, yB, sM, pO
Spruce-fir (SPBF_26)				rS, bS, bF, wS, wP, rP, rM, eC, wB, yB
White pine (WP)				wP, rS, rP, wB, rM, pO, eC, bF
Tamarack-larch (TL)				tL, rS, wS, bS, wB, bF, wP, pO, rM
	Softwood – intolerant Hardwood (SWIH_25_33)			bF, rS, rM, wB, pO, bS, wP, eC, hE, probe
	Softwood – intolerant Hardwood (SWIH_26)			rS, rM, wB, bF, yB, pO, eC, wP, wS
	Softwood – tolerant Hardwood (SWTH)			rS, rM, bF, yB, wP, rP, wS, bE, pO, tL, hE, eC
		Intolerant hardwood – Spruce (IHSP)		wB, rM, rS, bS, yB, pO, bF, eC, hE, bE, sM
		Tolerant hardwood – Fir (THBF)		rM, bF, yB, rS, pO, wB, sM, wS, wP, hE, bE, bS
		Tolerant hardwood – Spruce (THSP_25_33)		rM, rS, bS, bF, pO, wB, sM, yB, bE, wP, rP, eC, hE, wS
		Tolerant hardwood – Spruce (THSP_26)		rM, rS, sM, yB, bS, bE, wB, bF, wS, eC
			Intolerant hardwood – Tolerant hardwood (IHTH)	wB, rM, yB, pO, rS, sM, bF, bE, bS, wS, wP, eC
			Intolerant hardwood (INHW)	wB, rM, rS, pO, yB, bF, bS, eC, bE, wS
			Tolerant hardwood (TOHW_25_33)	sM, bE, rM, rS, yB, wB, hE, eC, bF
			Tolerant hardwood (TOHW_26)	sM, yB, rM, rS, bE, wB, bS, wS, bF

[z]**Species codes: bF** – balsam fir [*Abies balsamea* (L.) Mill.], **rM** – red maple (*Acer rubrum* L.), **sM** – sugar maple (*Acer saccharum* Marsh.), **yB** – yellow birch (*Betula alleghaniensis* Britton), **wB** – white birch (*Betula papyrifera* Marsh.), **bE** – beech (*Fagus grandifolia* Ehrh.), **tL** - tamarack/larch [*Larix laricina* (Du Roi) K. Koch], **wS** – white spruce [*Picea glauca* (Moench) Voss], **bS** – black spruce [*Picea mariana* (Mill.) B.S.P.], **rS** – red spruce (*Picea rubens* Sarg.), **jP** – jack pine (*Pinus banksiana* Lamb.), **rP** – red pine (*Pinus resinosa* Ait.), **wP** – white pine (*Pinus strobus* L.), **pO** – trembling aspen (*Populus tremuloides* Michx.), **hE** – eastern hemlock [*Tsuga canadensis* (L.) Carr.], **eC** – eastern white cedar (*Thuga occidentalis* L.)

[y]Eco-districts were used to delineate some strata; e.g., SPBF_2533 represented a spruce-fir stratum in eco-districts 25 and 33, whereas SPBF_26 represented a stratum in eco-district 26. Strata without a numeric suffix were applicable to the entire landbase of CFB Gagetown's three eco-districts: 25, 26, and 33, as shown in Fig. 2.

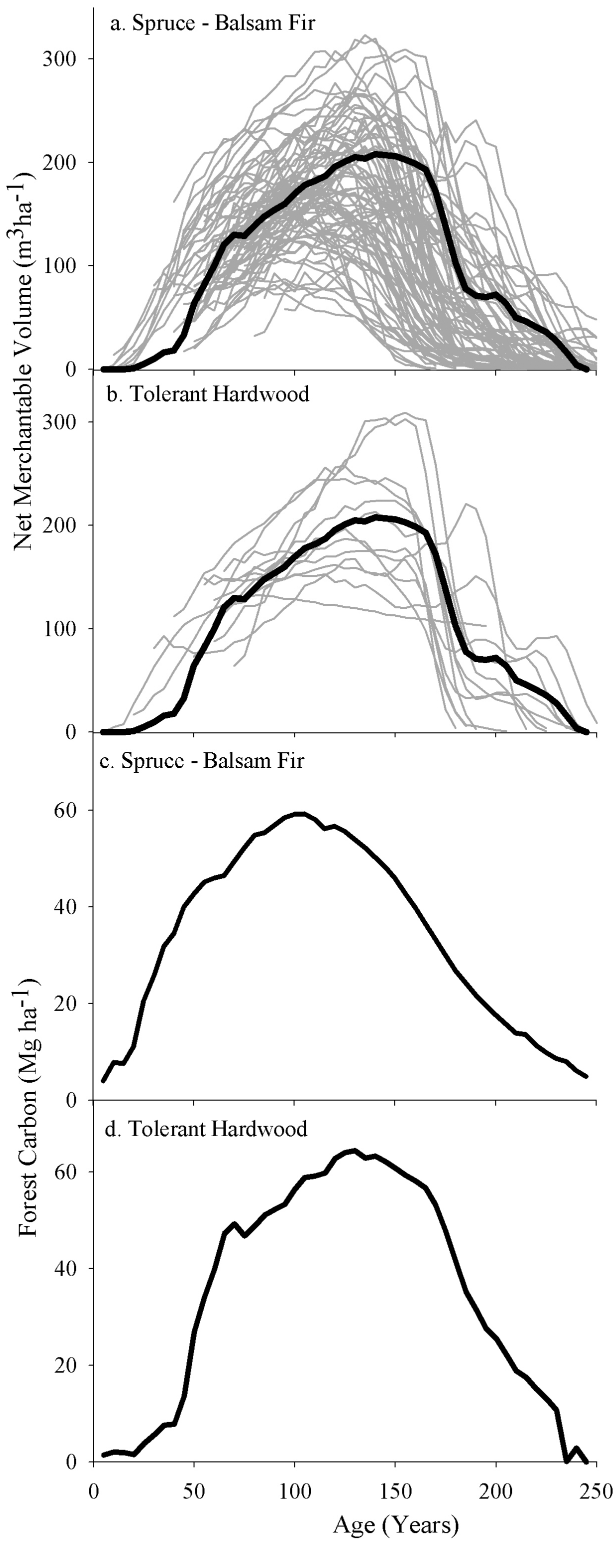

Fig 4. Examples of two merchantable volume yield curves developed using the STAMAN growth and yield model, and C yield curves derived from them. Bold lines represent average yield curves as used in the timber supply model; light grey lines represent individual FDS plot data.

ming biomass for the entire landbase, the C stocks on the landscape were calculated.

The use of biomass functions and the "resetting" of these functions to near-zero values post-clearcut disturbance will undoubtedly cause some error in the quantification of C stocks. The nature of the Woodstock model dictates that following stand-replacing disturbances, like clearcutting, stands are transitioned following a matrix of regeneration expectations. For example, a spruce-fir stand type post-clearcut may regenerate 60% to a spruce-fir stand type and 40% to a tolerant hardwood stand type. In essence, the initial area of spruce-fir is split into 60% of its original area, with 40% of the area now assumed to be regenerating as a tolerant hardwood stand type. In terms of merchantable volume, this does not represent a problem as each of the merchantable volume curves starts at age zero and thus merely transitioning stand types does not artificially create volume. C stocks estimated using the Woodstock model, however, may be overestimated as the biomass curves rarely go to zero. However, early successional C stocks in this analysis were low (0–10 Mg C ha^{-1}) and thus the model would find little incentive to manage the landbase for these conditions. This was partially confirmed in our results, as the model favored an older age-class structure for forest C management.

Soil Carbon

Soil C (contained in mineral soil beneath the forest floor) was not considered in the simulation due to the uncertainty of amount of soil C in strata at CFB Gagetown and the relative lack of change in this large C pool. Uncertainty surrounding soil C could be more accurately addressed using another method, perhaps using artificial neural networks and soil sampling data. Soil C stocks (humus) simulated by CO_2Fix were removed from the simulation of time-dependant biomass yields. We chose to include the forest floor litter layer as it was derived from the above-ground-biomass. Soil C represents two-thirds of the world's terrestrial C stocks (Houghton 2003) and should be considered by forest management. However, this paper will only outline C in above-ground vegetative sources as well as belowground roots.

Objective Functions and Constraints

The CFB Gagetown management objectives were used as the baseline for comparisons. Four different management scenarios were examined, each with two different sets of constraints. The objective functions and constraints are outlined in Tables 2 and 3. Within the past 25 years, CFB Gagetown forestry activities have resulted in approximately 320 ha yr^{-1} (1600 ha 5-yr^{-1} period) being harvested. This amount of area harvested was used as a constraint in objective functions 1–4 (Table 3) in simulating scenarios. The total merchantable volume in the study area during the past 15 yr of the planning horizon was constrained to be non-declining, thus creating a legacy of timber beyond the planning horizon and helping to ensure sustainability. Management harvested approximately 15% of the total area by partial cutting, and this was used as another constraint. Steady supplies of timber were historically needed to supply local contractors and mills, thus creating an even-flow volume-

Table 2. Constraints used in the wood supply model for CFB Gagetown. The area harvested constraints simulated historic harvesting levels at CFB Gagetown

Constraint	Duration	Constraint label
Area harvested ≥300 ha yr^{-1}	Entire planning horizon	a
Area harvested ≤ 340 ha yr^{-1}	Entire planning horizon	b
Non-declining volume	Final 15 yr of the planning horizon	c
Non-declining operable growing stock (volume available to be harvested)	Final 15 yr of the planning horizon	d
Area partially cut must be ≤ area clearcut	Entire planning horizon	e
Volume harvested must vary by no more than 5 percent above or below previous 5-yr level.	Entire planning horizon	f

Table 3. Objective functions used in the wood supply model of CFB Gagetown for simulations

		Constraints					
Scenario description	Objective function	a	b	c	d	e	f
Baseline	1 - Maximize revenue – Gagetown constraints	•	•	•	•	•	•
Max discounted revenue	2 - Maximize 4% discounted revenue – Gagetown constraints	•	•	•	•	•	•
Max discounted C	3 - Maximize 4% discounted C Gagetown constraints	•	•	•	•	•	•
Goal programming under CFB Gagetown's constraints	4 - Goal 1- revenue of \$1.8 · 10^6 yr^{-1} Goal 2 attain 5 · 10^5 Mg C yr^{-1}	•	•	•	•	•	•
Max discounted revenue - no area harvested constraints	5 - Maximize 4% discounted revenue			•	•		•
Max discounted C - no area harvested constraints	6 - Maximize 4% discounted C stocks			•	•		•
Goal programming with no area harvested constraints	7 - Goal 1-attain \$ 2.6 · 10^6 yr^{-1} Goal 2-attain 5 · 10^5 Mg C yr^{-1}			•	•		•

harvested constraint, which limited variation to ±5% per period throughout the planning horizon.

Seven objective functions were used to assess the range of management actions and their effects on landscape C stocks. Four objective functions, or scenarios, had the area harvested constraint based upon CFB Gagetown current harvesting levels. Other scenarios maximized revenue discounted at a 4% rate and maximized C stocks discounted at a 4% rate. A goal programming (GP) scenario designed to meet the CFB Gagetown average revenue generation and generate the highest possible C stocks provided a "balanced" scenario in which revenue and C acted as co-dominant objectives for the linear programming solver to solve. We also simulated the CFB Gagetown current management objectives to provide a baseline for comparison (Table 3). Three of the objective functions were used without area harvested constraints to show the best and worst case scenarios in terms of C sequestration and revenue generation. With the area harvested constraints applied to objective functions 2–4, the construction of the objective functions and linear programming were responsible for the change in values of indicators for C and revenue.

Goal Programming Model

The GP model was applied as a weighted GP with penalties for over or underachievement of the stated goals. The weighted penalties were described as:

WC_o, WC_u
WR_o, WR_u

where WC_o and WR_o are the weighted penalties for overachievement of the goals associated with forest C and net revenue, respectively. WC_u, WR_u are the weighted penalties for underachievement of the goal of forest C and net revenue, respectively.

C_t, R_t

where C_t, R_t are the representative variables of net revenue and forest C at period t, respectively.

RO_t, RU_t
CO_t, CU_t

RO_t, RU_t and CO_t, CU_t represent amounts over, or under, the stated goal of R_t and C_t. These are the deviation variables that the GP model was set to minimize. The GP model then becomes:

$n = 16$

$$Min\sum_{t=1}^{n}\left[WC_oCO_t + WC_uCU_t + WR_oRO_t + WR_uRU_t\right] \quad (1)$$

The coefficients of the weights of the GP model outlined in Table 3 were as follows: objective function 4 – WC_o 0, WC_u 100, WR_o 0 and WR_u 10; objective function 7 – WC_o 0, WC_u 300, WR_o 0 and WR_u 10. The weights of overachievement were set at zero to allow the model to overachieve the goal without penalty. However, due to the high coefficients on the penalties for underachievement, and due to the conflicting nature of the two variables (C and revenue), in which increases in one would result in decreases to the other, the model would only meet the stated goals as outlined in Table 3 and would not overachieve.

Discount Rates

We applied discount rates to revenue and C to reflect the economic rate of discount on management objectives. Discounting C gave the model incentive to sequester C at the start of the planning horizon, as future values of C sequestered would appear less valuable to the model due to the discount rate. Four percent was chosen as the rate of discount, as it was used by van Kooten et al. (2004) and Murray (2000) in calculations of cost of C emissions offsets and is representative of a value that has been used in other studies. Not discounting C would imply that since there was little incentive to sequester C at present, in the near future, or over the long-term, then there is little incentive to sequester C at all (van Kooten et al. 2004). However, we recognize that there will be incentive to sequester C in the absence of a discount rate. Using a discount rate provided the model with incentive to address the Kyoto Protocol commitment period of 2008–2012, during which changes in forest C stocks will represent direct emissions. Discount rate or not, C sequestration for the planning horizon will be an incentive in the formulation of the objective function solved by the model.

RESULTS AND DISCUSSION

Harvest Levels and Carbon Stocks

Simulated levels of C were most directly influenced by the amount of volume harvested. Higher revenues were the result of larger volumes of timber being extracted from the forest. Figure 5 shows the relationship between volume harvested, and the simulated C stocks; the less variation within the volume harvested, the less variation between the simulated C stocks. The C stocks reached their highest value with the objective function set to maximize C, discounted at 4% (Fig. 5a). Not harvesting was simulated and did produce the highest C stocks on the landscape (though not shown in the figure), but this was not an option for a forest management department that had commitments to deliver wood products to the surrounding community. Also, not harvesting may have produced the highest C stocks simply because of the current age class structure of the forest. As shown in Fig. 6, the initial age class structure was quite young, and not harvesting would simply age the forest by 80 yr. This is assuming there were no major natural disturbances such as forest fires or large-scale pest outbreaks, not considered in this simulation, which would lead to large amounts of C returning to the atmosphere through decomposition or combustion. Maintaining an older aged forest may not be sustainable as, eventually, older stands will succumb to break-up and be replaced by successional species. Certainly though, the more C that remains on the landscape in woody form, the greater the risk to C from pest infestation or large-scale forest fires. Kurz et al. (2002) postulated that increased disturbance rates would shift the age class structure to the left, as was evident in our Fig. 7d results. This could result in the forest overall becoming a net source of greenhouse gases; forest C levels showed a distinct drop under the scenario to maximize net present value of forest products (Fig. 5a). Murray (2000) also found that as the price of C increased, the rotation age of planted pine increased.

Maximizing C Stocks

The greatest increase of C stocks from the start of the planning horizon to its end resulted from the model with the objective function to maximize C discounted 4%. This was expected and the outcome of the simulation resulted in an older age class structure at the end of the planning horizon (Fig. 7c). The model achieved high levels of C stocks by increasing the rotation age, by partial cutting, and by allowing the forest to evolve into old (≥ 100 yr of age) age classes. Harvesting was conducted in this scenario using constraints that ensured a non-declining yield of volume in the last 15 yr of the planning horizon. Without this constraint, the forest would begin to lose volume to senescence, and therefore could not meet the constraint of a non-declining volume yield. Lee et al. (2002) found that in the 5 yr following a partial cut compared with a clearcut, litterfall rates in the partial cut stands were higher, increasing nutrient cycling rates and resulting in less reduction in the depth of the forest floor. Our results also suggested that increased C sequestration is possible with partial cutting, supporting increased litterfall rates versus areas clearcut. However, partial cutting requires operator dexterity to protect non-harvested trees, and return trips to the forest for the second rotation of the partial cut would be necessary (Lee et al. 2002). Sohngen and Mendelsohn (2003) determined that increased rotation lengths resulted in higher forest C sequestration, which is consistent with our results, where the age class structure of the scenario with highest forest C levels was notably older (Fig. 7c).

Maximizing Discounted Revenue

Simulated mazimized discounted revenue resulted in the greatest return on investment, yet showed significantly decreased landscape C stocks (Fig. 5a). Maximization of revenue conflicts with C sequestration objectives, which represents a challenge should forest managers try to accommodate both values. Maximization of revenue resulted in the highest levels of clearcutting and partial cutting, simply due to the monetary weight associated with timber harvested. Under the CFB Gagetown area harvested constraint (300–340 ha yr^{-1}) the maximization of discounted revenue only slightly outperformed the CFB Gagetown baseline scenario (Fig. 8a). The area harvested constraint rendered the maximization of discounted revenue virtually ineffective in comparison with the scenario with no constraints on the area harvested. This was due to the discount rate, as discounting will force future revenue to appear less valuable to the model than revenue generated at the start of the planning horizon. By removing the area harvested constraint and simulating maximized discounted revenue, it was possible to see how much the model was constrained by the amount of area allowable for harvest (Fig. 8b).

Goal Programming

The GP objective function was derived to create a balance between the best case scenarios the model simulated economically and in terms of C sequestration. Diaz-Baltiero and Romero (2003) suggested dealing with multiple outputs of forest management, C sequestration, and timber produc-

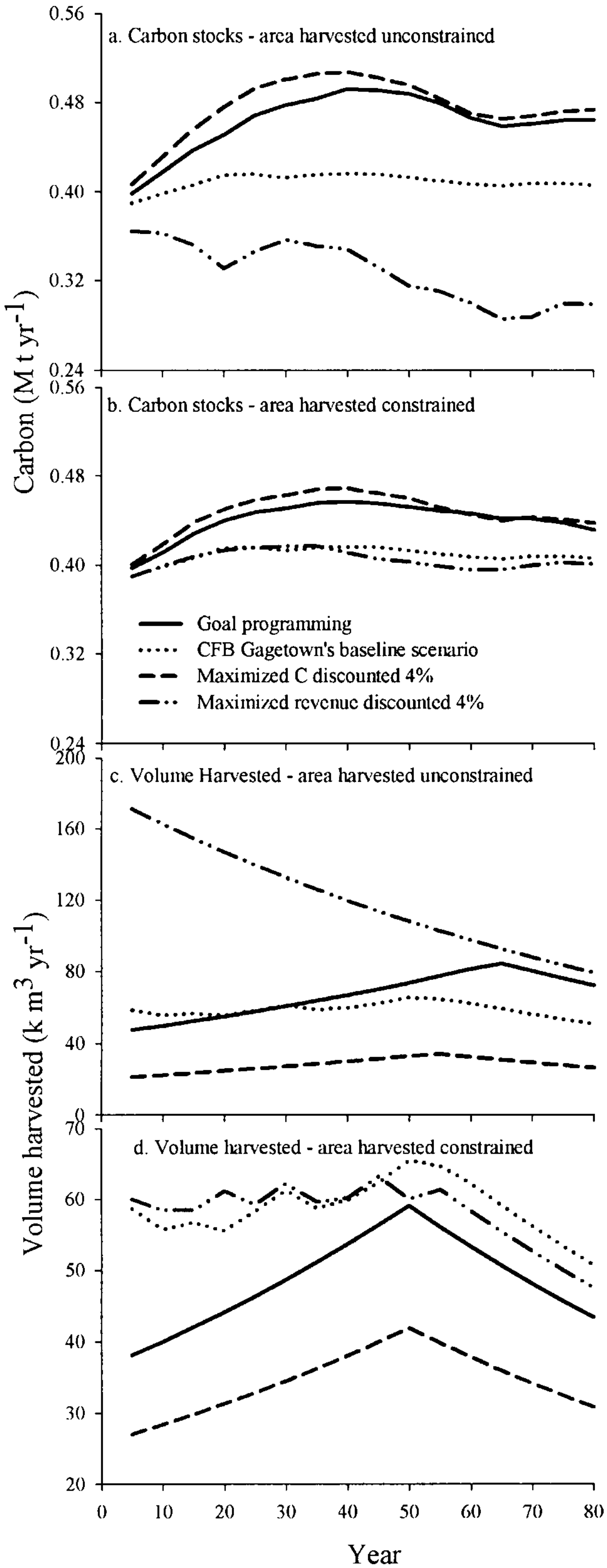

Fig. 5. Harvesting levels and C stocks as simulated by the timber supply model.

Fig. 6. Initial age class structure of the forest at CFB Gagetown.

tion using GP methods. They showed how C sequestration objectives could easily be integrated into current optimisation models and we undertook a similar approach. GP also provides the optimisation model with added flexibility, as solutions to multi-criteria objective functions are rarely infeasible. Using "hard" constraints for forest C levels resulted in frequent infeasibility issues with the solution of the objective function. Bertomeu and Romero (2001) suggested reformulation of objective functions into a GP model to avoid infeasibility issues. GP minimizes the deviations from the stated goals of the objective function. In this case, the average revenue generated under the CFB Gagetown current management scenario was approximately \$1 800 000 yr^{-1}, and this was used to formulate the first goal of the objective function for simulation with the area harvested constrained. Without the area harvested constrained, it was possible to increase the first goal to a level of \$2 600 000 yr^{-1}. The second goal was set at a C stock level of 500 000 Mg C yr^{-1}, based on the average C stocks generated under maximization of C discounted at 4%. This goal for C stocks was kept the same without the area harvested constraint, as achieving levels above the goal were generally infeasible.

It is evident (Figs. 5 and 8) that the GP approach reached a compromise between management for revenue and management for increased C stocks. Diaz Baltiero and Romero (2003) also determined that reductions in net present value would result when management for forest C was undertaken. Our results showed a resulting forest age class structure with large areas of both young and old forest (Fig. 7b). The cost of considering C a goal of management is outlined in Fig. 9. The GP scenario achieved its balance by creating a forest structure that was old, yet when the model simulated harvests, it concentrated on high-value end products like softwood and hardwood sawlogs. Sawlogs were concentrated in stands that were partially cut and the model favored partial cutting in this scenario (Fig. 10b). Harvesting sawlogs served to keep C from the atmosphere, because wood products produced from sawlogs generally take longer

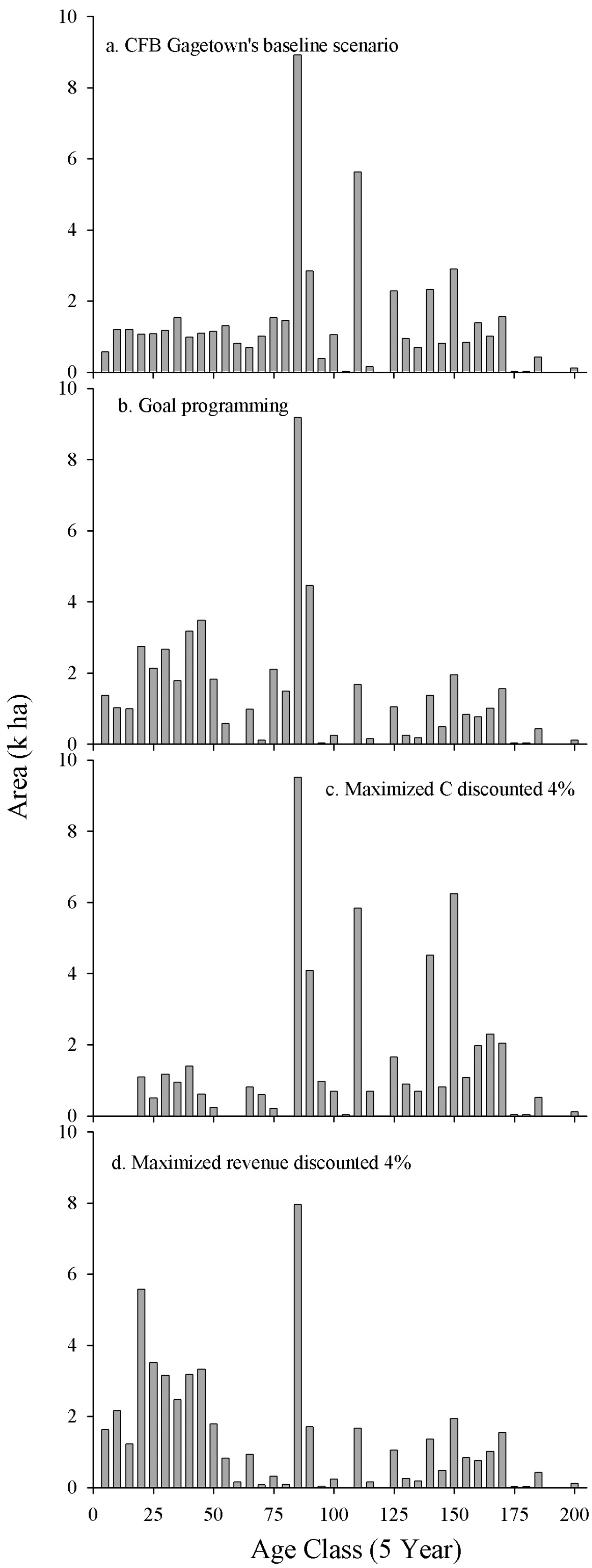

Fig. 7. Resultant simulated forest age-class structure after four different management scenarios at year 80 of the planning horizon.

to decompose to the atmosphere than pulpwood products (Apps et al. 1999). However, under the Kyoto Protocol, pending the Canadian Government decision to include forest management in the emissions accounting process, any C removed from forests is considered as directly emissioned to the atmosphere.

Cost of Managing for C Stocks

The cost Mg^{-1} of C (Fig. 9) represents the revenue lost when management is changed to include C sequestration as a goal. This cost was calculated as the weighted average of (1) the difference in revenue generated in the CFB Gagetown current management scenario and that in the GP scenarios, and (2) the difference in C stocks between these two scenarios. Lewis et al. (1996) evaluated the costs of managing forest ecosystems to sequester carbon, and found that the potential was largely influenced by climatic and site conditions. Our study area represents relatively low-yielding forest, which influences the ability to generate revenue from forest products. Lewis et al. (1996) concluded that the cost of managing forest for C storage was most feasible in the northeast of the United States due to the large areas of hardwood forest.

Each Mg of C gained from new management actions could be considered a C credit in compliance with the Kyoto Protocol, with the nature of the C credit generated by enhancing forest sinks or reducing forest sources through forest management dependent upon (1) whether Canada elects Article 3.4 of the Kyoto Protocol (i.e., to include C sinks and sources from areas subject to forest management in the national greenhouse gas accounts for the first commitment period), and (2) how domestic emissions trading systems are set up. Managing the forest for higher C stocks resulted in losses in revenue due to sub-optimal harvest rotation periods (Fig. 8a, b), and this was also found by Murray (2000). The cost Mg^{-1} of C went down the longer the implementation of the management plan (Fig. 9). The cost of implementing the GP approach with no harvesting constraints was approximately 70$ Mg^{-1} of C sequestered, and by year 20, the cost dropped below \$20 Mg^{-1}. When the cost of C dropped below zero, it was no longer considered a cost to management, but this does not imply that revenue was created simply by C. As the cost of management for C dropped, it meant that management was becoming more efficient in considering C as an objective, and it was only as a result of management that the cost dropped, not implying that future revenue would be generated only from C stocks. In any case, the cost Mg^{-1} C in this study was within the range calculated by van Kooten et al. (2004), although the revenue generated (Fig. 8) did not take into account the cost of road construction, which would underestimate the cost of managing for C. Also, emissions trading schemes could provide a price for C, thereby changing the economics of this analysis. The outcome of the simulations under the objective of maximizing discounted revenue might differ if forest managers could generate revenue by sequestering C and trading these C offsets to emitters from other sectors. Early indications suggest that a tonne of CO_2-equivalent could trade for several dollars, giving forest managers an alternate way of generating revenue from their landbase and poten-

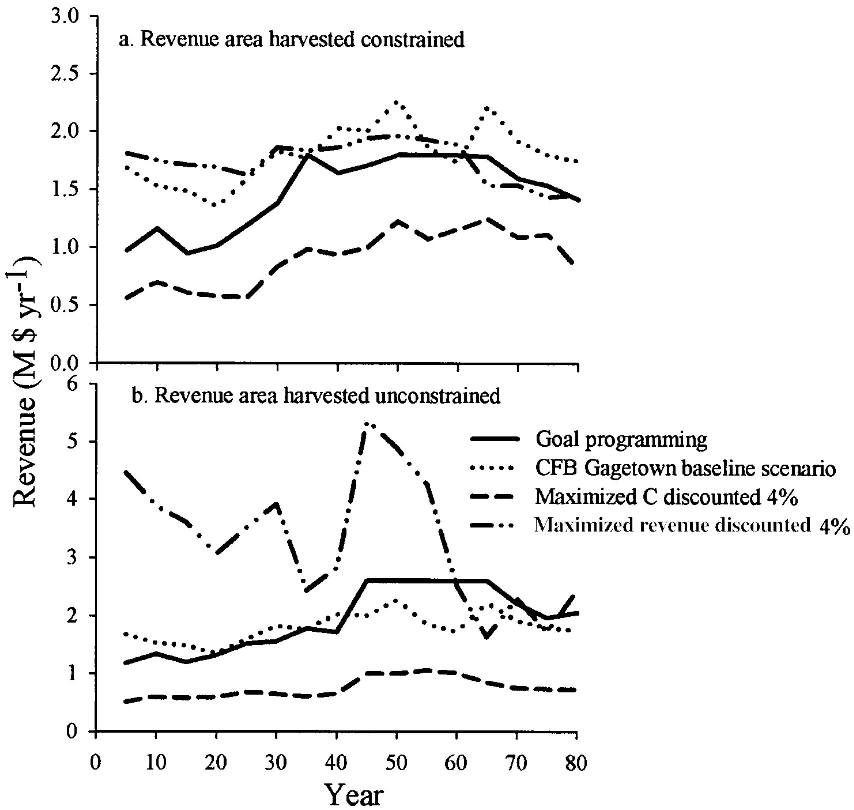

Fig. 8. Simulated amounts of revenue generated under the seven scenarios.

tially transforming the "cost" associated with considering C a goal of management into a revenue. Murray (2000) provided a more in-depth examination of forest management and cost of C topics.

The application of C yield curves in Woodstock is unlikely to fully conserve C. There may be instances, due to the nature of C stocks and volume being two very different indicators, in which simulated C stocks are being created merely from transitioning of stands to various regeneration curves. The Woodstock modeling environment allows for each stand type to regenerate to up to many (more than 20) different new stand types. In this process, yield curves are reset to age 0 and merchantable volume begins to grow according to whichever yield curve has been applied to its stand type. Merchantable volume usually begins at zero at age 0, however, C rarely goes to 0 at early ages. Due to this fact, C may not be conserved in transitioning from stand-replacing disturbances like clearcutting. Quantitatively determining the magnitude of this issue is difficult, but qualitatively, there may be an opportunity for small-scale gains in creative transitioning by the model. However, model runs in which C was given high priority resulted in an older age-class structure of the resulting forest. During such model runs, transitioning was minimized as stands were allowed to age to mature and over-mature conditions. This is certainly an inaccuracy in this modeling framework that could be addressed using CBM-CFS3 (Kurz et al. 2002), which is able to simulate harvesting schedules developed in Woodstock. However, CO_2Fix is unable to simulate large-scale harvesting schedules like the ones developed in this analysis.

In this study, we combined pools simulated by CO_2Fix into one C yield. This process could be separated and a C yield for each simulated pool (e.g., snags, forest floor litter, CWD) could be calculated. In ongoing work, we are using CFS-CBM3 (Kurz et al. 2002) to produce C dynamics of stands for use with forest estate modeling software such as Woodstock. Seely et al. (2004) outlined a spatial approach to forest management and C sequestration objectives that offers a more in-depth approach to ecosystem C calculations by employing a process model (FORECAST) and an empirical model. Spatial soil C could be calculated using artificial neural networks, GIS and soil sampling, which would address some of the uncertainty underlying soil C stocks. van Kooten et al. (2004) argued against using soil C stocks as a basis for calculating C offsets. C offset programs have begun in developing countries (Nelson and de Jong 2003) and these could use methods outlined in this paper to evaluate forest C stocks. These programs have resulted in a new C economy, in which farmers and landowners can deposit and withdraw C equivalents from a C "bank" (Nelson and de Jong 2003).

CONCLUSIONS

This paper outlined the basics for integrating C sequestration objectives into forest management planning. It is in no

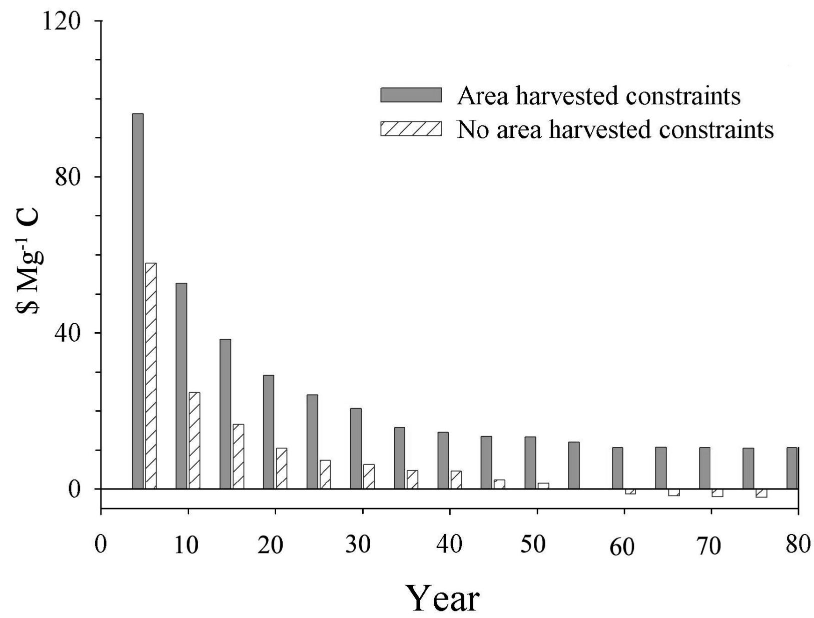

Fig. 9. The cost per tonne of C under CFB Gagetown's area harvested constraints and without the area harvested constraints, both under goal programming scenarios.

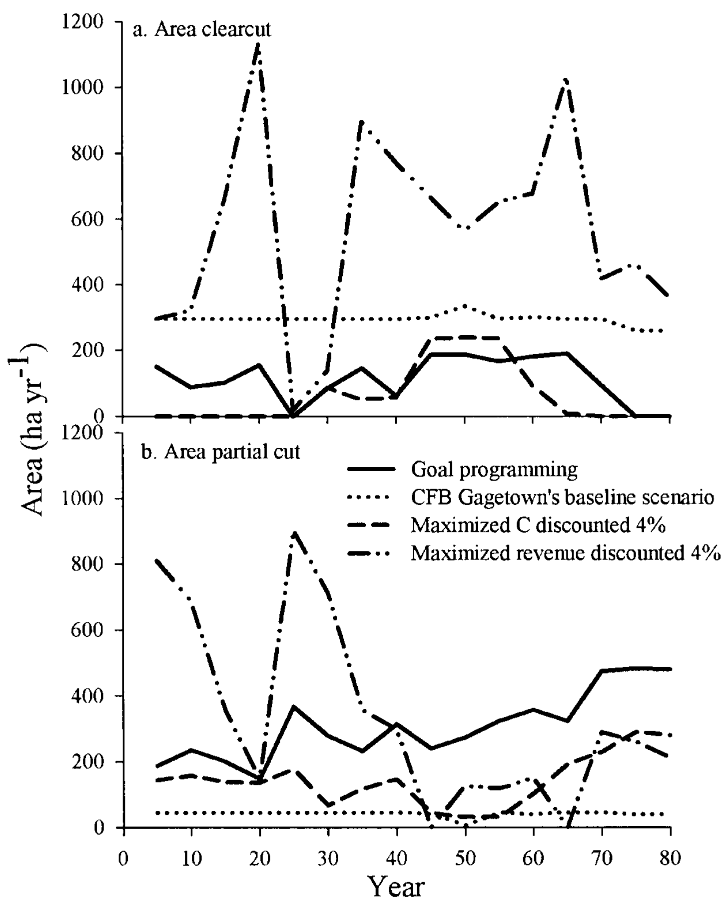

Fig. 10. Area harvested by two types of harvesting systems, partial cutting and clearcutting.

way complete in its account of all of the processes in the C cycle that are at work in the forest and subsequent forest end-products. However, it represents a first step in integrating C into forest management plans.

Our results suggest that partial cutting and concentrating harvesting on higher-valued sawlog end-products are the methods of choice in managing forest lands for C stocks, while maintaining traditional levels of revenue generation. More emphasis on production of sawlog products by forest industries is occurring in many parts of Canada, as large pulp mills begin to be economically unstable due to globalization and competition with countries that can produce pulpwood with much shorter rotation periods. Partial cutting for niche market end-products could provide an economic alternative to large-scale pulp production, while still offering a positive contribution to maintaining C stocks on the landscape. It should be noted, however, that partial cutting often involves more road construction to cover a larger area, and less volume per hectare removed than does a clearcutting system, and thus may result in more emissions from road building. Partial cutting systems would lead to more infrastructure in the forest to access more area to produce similar harvest levels. However, partial cutting has been shown to leave more C in the form of woody material (Lee et al. 2002). A detailed analysis of emissions created during harvesting should be investigated to fully conclude whether partial cutting is indeed a more attractive alternative to sequestering C.

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